

CLEAN ENERGY INNOVATION AT NREL

Continuum

SUSTAINABLE TRANSPORTATION



DAN SAYS

TRANSFORMING TRANSPORTATION

This issue of *Continuum* focuses on our contributions toward creating a sustainable transportation system—from developing more efficient electric and hydrogen fuel-cell vehicles to inventing technologies and processes for producing biofuel alternatives to gasoline, diesel, and even jet fuel.

In some ways, the challenges we face in transforming our nation's vehicle fleet and transportation infrastructure are more daunting than those we are overcoming in developing and integrating renewable electricity sources from solar, wind, and geothermal energy.

However, it is critical that we do so. Our transportation system accounts for more than 70% of petroleum consumption in the United States, and more than 30% of our total carbon emissions. Unlike electricity, there is no primary transportation energy "grid" with a network of power plants. Independent oil refineries produce carbon-intensive fuels that then travel by train and truck to thousands of filling stations across the country.

Truly transforming the existing transportation infrastructure to create cost-effective and sustainable alternatives will require close collaboration between government and industry, and a significant shift in consumer attitudes. Is a new transportation future even possible?

THE POWER TO REDUCE OUR DEPENDENCE ON OIL

At the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL), we believe the answer is yes.

We recently completed a landmark transportation study in collaboration with Argonne National Laboratory and sponsored by DOE's Office of Energy Efficiency and Renewable Energy (EERE). The Transportation Energy Futures Study (TEF) demonstrates that we have the potential to reduce our dependence on oil and lower greenhouse gas emissions by more than 80% by 2050.

While these deep reductions are indeed possible, the TEF study makes it clear that achieving them will require a combination of strategies. These include increasing the use of biofuels, and lessening the demand for transportation. It will also include an expanded role for electric and hydrogen technologies.

NREL's unique leadership in transportation research focuses on heavy-duty trucks, as well as passenger vehicles, exploring ways to make gas-powered vehicles more efficient, and developing the technology needed to put more electric and biofuel vehicles on the road. Like our other clean energy research, NREL's transportation expertise is integrated across many disciplines including thermal management technologies for electric-drive components and systems, battery design, and hydrogen fuel-cell manufacturing test processes.

Our scientists are on the next frontier of bioenergy research, developing "drop-in" biofuels that can displace fossil fuels—without requiring modification of our existing fuel infrastructure. NREL is also home to the National Bioenergy Center, where we operate pilot biorefinery facilities to assist private industry in developing cellulosic ethanol formulas and production methods for turning crop and wood wastes into renewable fuels.

I invite you to read about those efforts and more. Transforming how we drive and power our vehicles is not only possible but, we believe, on the horizon. Through scientific innovation, industry partnerships, and accelerated deployment, NREL will lead the way to a sustainable transportation future.

Dr. Dan E. Arvizu, Laboratory Director



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National Parks Initiative greens roads and preserves once-in-a-lifetime experiences.

Photo by Dennis Schroeder, NREL



Powered by a fuel cell system with light-weight, high-pressure hydrogen tanks, an electric motor, a nickel-metal-hydride battery, and a power-control unit, the Toyota fuel cell electric vehicle has zero tailpipe emissions.

FUEL CELL ELECTRIC VEHICLES: PAVING THE WAY TO COMMERCIAL SUCCESS

Research focuses on boosting reliability, reducing costs, and designing infrastructure of the future.

AS NATIONS around the world pursue sustainable transportation solutions, the hydrogen fuel cell electric vehicle (FCEV) presents a promising opportunity for consumers and automakers alike. Automakers have made steady progress reducing the cost and increasing the performance of fuel cell propulsion systems, and most major vehicle manufacturers are geared to launch FCEVs in the U.S. market between 2015 and 2020.

Although fuel cell technologies are proven and effective, deployment challenges persist—particularly in terms of further reducing the cost and increasing the durability of fuel cells and getting sufficient infrastructure in place to support widespread consumer use. Researchers at the National Renewable Energy Laboratory (NREL) are collaborating with industry partners to remove some of these barriers.

IN-LINE DIAGNOSTICS HELP REDUCE COST, IMPROVE RELIABILITY

As the fuel cell manufacturing industry moves from small- to large-scale production, quality control is essential. Using NREL-developed in-line diagnostics, manufacturers can more effectively identify defects in fuel cell components, leading to higher production volumes, improved reliability, and lower costs.

"The cost impact of defects could be huge," said Senior Engineer Michael Ulsh. "A fuel cell stack can consist of hundreds of components. Because a single component failure could affect the whole stack, a 10% composite stack failure rate could drive up stack cost by 60%."

To help address this challenge, researchers use an NREL-developed optical reflectance system to identify defects in fuel cell membranes and apply active infrared imaging techniques to identify defects in electrode materials. These methods have been validated on a small-scale manufacturing line that can convey fuel cell component materials at speeds of 100 feet per minute.

SUPPORTING A HYDROGEN INFRASTRUCTURE ROLLOUT

NREL recently joined H₂USA, a public-private partnership designed to promote the widespread adoption of FCEVs. This new partnership focuses on overcoming the hurdles associated with establishing a robust hydrogen infrastructure.

"NREL's participation in this partnership builds on the lab's extensive fuel cell and hydrogen technology validation and analysis experience," said Jen Kurtz, manager of the hydrogen analysis group. "Our hydrogen systems analysis staff will collaborate with a team of analysts from other national labs, universities, and key stakeholder groups to evaluate infrastructure rollout strategies and the business case for commercialization."

This team will combine analytic capabilities refined over many years of systems analysis to understand the technical, market, and investment challenges associated with the transition to hydrogen, electric, and other alternative fuel vehicles. NREL will contribute a suite of modeling and analysis capabilities developed over the last decade in support of the U.S. Department of Energy's Fuel Cell Technologies Office as well as technology validation; safety, codes, and standards; and market transformation expertise.



Photo by Dennis Schroeder, NREL

NREL's Keith Wipke explains how a fuel cell electric vehicle works at an advanced vehicle ride-and-drive event at the NREL Education Center.

"NREL's participation in this partnership builds on the lab's extensive fuel cell and hydrogen technology validation and analysis experience..."



Photo by John De La Rosa, NREL

Fuel cell electric vehicles fill up at NREL's hydrogen fueling station, which dispenses hydrogen made via renewable electrolysis.

RENEWABLE HYDROGEN FCEVS

Because hydrogen can be made from a variety of domestic resources, FCEVs reduce our nation's dependence on imported oil and diversify our transportation-related energy sources. While most hydrogen is currently produced from natural gas, NREL is investigating renewable hydrogen production technologies that tap into energy from the sun and wind.

"Here at NREL, we have four FCEVs on loan from Toyota that fill up on renewable hydrogen—wind turbines and solar arrays power electrolyzers that split water into hydrogen and oxygen," Kurtz said. "We showcase these and other advanced vehicles at public events to raise awareness about the alternative transportation options available today and on the horizon."

—Written by Julia Thomas



In NREL's new Energy Systems Integration Facility, the Insight Collaboration Laboratory shows a 3D model of cellulose microfibrils.

AT \$2.15 A GALLON, CELLULOSIC ETHANOL COULD BE COST COMPETITIVE

DOE challenge met—research advances cut costs to produce fuel from non-food plant sources.

IMAGINE a near perfect transportation fuel—it's clean, domestic, abundant, and renewable. Now imagine that it's also affordable.

Bringing this vision closer to reality was the challenge the U.S. Department of Energy's (DOE) Advanced Energy Initiative presented to the National Renewable Energy Laboratory (NREL) in 2006. NREL met this challenge in 2012 by demonstrating that it is possible to produce cellulosic ethanol—ethanol from non-food plant sources—in a way that is cost competitive with other transportation fuels.

DOE's Office of Energy Efficiency and Renewable Energy's (EERE) Bioenergy Technologies Office selected NREL to work toward the cost target because of the laboratory's strong reputation in biofuels technology.

"NREL is the world's leading institution in biofuels research, analysis, and development," said National Bioenergy Center Director Tom Foust. "I don't think there is another organization that would have been as capable of pulling this off. We have exceptional staff and state-of-the-art facilities."

After several years of modeling, performing biomass-to-fuels conversion test runs, and compiling and analyzing market data, NREL has been able to demonstrate actual scenarios that meet the \$2.15/gallon by 2012 cost goal—the goal the Advanced Energy Initiative set to demonstrate that cellulosic ethanol could be competitive with corn ethanol and conventional fuels.

"It was a concerted effort," Foust said, when explaining the focus required to carry out the six-year run. "It was an unprecedented commitment to a goal by the lab, and to the lab by EERE."

"I don't think there is another organization that would have been as capable of pulling this off. We have exceptional staff and state-of-the-art facilities."

TWO PLATFORMS, ONE OBJECTIVE

Achieving this goal wasn't just an isolated victory. NREL has been able to meet the cost goal using two separate conversion platforms: biochemical and thermochemical. The biochemical process can produce ethanol at a minimum ethanol selling price of \$2.15/gallon. The thermochemical platform demonstrated a minimum ethanol selling price of \$2.05/gallon.

The biochemical path involves the degradation of cellulose and hemicellulose, into simple sugars through pretreatment and the use of enzymes. Microorganisms then ferment the sugars to ethanol and other alcohols.

The thermochemical process involves gasifying the biomass to "syngas" consisting of hydrogen and carbon monoxide, and then catalytically converting the syngas to ethanol.



NREL's recirculating
regenerating
reformer system
(R-cubed) provides
continuous
reforming of biomass-
derived syngas.

RISING TO MEET MARKET CHALLENGES



Photo by Dennis Schroeder, NREL

Samples of biomass catalysts are prepared for characterization in one of NREL's thermochemical laboratories.

NREL researchers worked simultaneously to meet the cost target and establish design platforms the private sector can use to accelerate the commercialization of cellulosic ethanol. And, indeed, the commercialization has begun. Facilities to produce cellulosic ethanol are under construction, including DOE-supported projects led by Abengoa in Hugoton, Kansas; POET in Emmetsburg, Iowa; and INEOS in Vero Beach, Florida.

While these industry investments are significant, Foust believes that cellulosic ethanol may not achieve the significance in the fuels market that industry, the research establishment, and the administration had hoped when it established the cost goal in 2006.

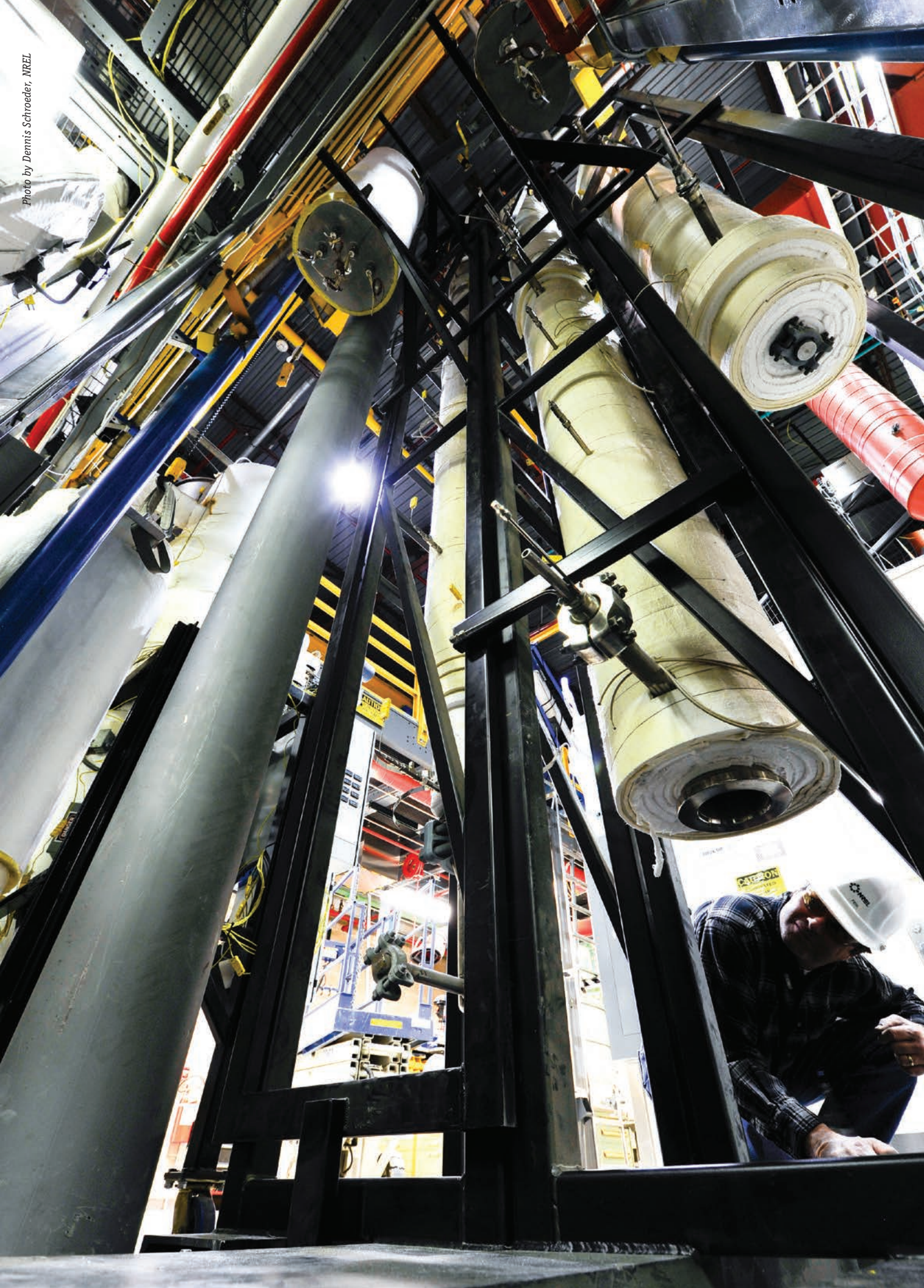
During the six years NREL and EERE worked to meet the goal, markets changed. Domestic ethanol production met the market demand for E-10, and E-15 did not penetrate the market as hoped.

"The biofuels market is in flux," Foust explained. "It goes through boom and bust cycles. The good news: NREL and EERE set an important goal and achieved it. We're recognized as top partners with the industry. Our reputation has never been stronger."

The strength of that reputation and the ability to meet significant goals are providing NREL with new opportunities. Next up: Biofuels stakeholders are working to convert cellulosic feedstocks into high performing drop-in biofuels that are compatible with existing infrastructure and nearly indistinguishable from gasoline, diesel, and jet fuel, and NREL is helping lead the way.

— Written by Kristi Theis

"NREL and EERE set an important goal and achieved it. We're recognized as top partners with the industry. Our reputation has never been stronger."



Can “DROP-IN” BIOFUELS Solve Integration Issues

Lab works to create biofuels indistinguishable from conventional petroleum-based fuels.



Ever since its inception 36 years ago, the National Renewable Energy Laboratory (NREL) has been working to develop biofuels that can displace petroleum-based fuels and lessen our nation's oil dependence. That's a difficult challenge because, ideally, a new fuel would need to be compatible with the pipelines, blending stations, and fuel pumps that form the U.S. fuel infrastructure, which required a massive capital investment and many years to develop.

OF COURSE, the fuel would also need to work well with vehicles, burning cleanly and providing the needed performance without causing damage. Failing to address these critical “integration issues” can make a fuel more difficult to distribute and use, potentially raising the fuel's cost and limiting its market.

The trick to avoiding such issues is to create new biofuels that, for all practical purposes, are indistinguishable from conventional petroleum-based fuels. To do so, biomass must be converted to hydrocarbon fuels, which consist of long chains of carbon atoms with many hydrogen atoms bound to that chain. Gasoline, for instance, is comprised

mainly of hydrocarbons with seven to eleven carbon atoms in a chain, or C7 through C11 for short. Kerosene and jet fuel are primarily C12 to C15, while diesel fuel contains longer-chained hydrocarbons.

Such “drop-in” biofuels could literally be added into the existing fuel infrastructure without any changes. While motorists would not notice a difference in their fuel, a growing percentage of that fuel would come from natural, renewable resources such as grasses and trees rather than petroleum.

“LEVERAGING THE EXISTING OIL REFINING INFRASTRUCTURE, THE PIPELINES, REFINERIES, STORAGE SYSTEMS, DISTRIBUTION, AND DISPENSING SYSTEMS, IS A GREAT ADVANTAGE FOR DROP-IN BIOFUELS.”

“Leveraging the existing oil refining infrastructure, the pipelines, refineries, storage systems, distribution, and dispensing systems, is a great advantage for drop-in biofuels,” said Rich Bolin, a manager for partnership development at NREL. “Oil refineries are incredibly capital-intensive; nobody has built a major, world-scale oil refinery in the United States since 1977, and the reason for

that is that they're just too expensive to build. Being able to produce a fuel intermediate or a finished fuel, by biological or thermochemical means, and feed it into a refinery at various points, lowers the production costs for those drop-in biofuels. Working with oil refineries will speed up the commercialization of drop-in biofuels and extend our crude oil resources.”

The question is where, exactly, to drop in those biofuels? Some of the processes used to develop biofuels produce a heavy oil that theoretically could be processed into fuel in an existing refinery, while other processes result in products similar to the fuels that we're more accustomed to: gasoline, diesel fuel, and jet fuel. These three petroleum fuels are often considered the trinity of major transportation fuels that keep this country, and the world, on the move.

We also need to figure out what to make the biofuels from and how best to produce the drop-in biofuels.



Photo by Dennis Schroeder, NREL

NREL Fuels Performance Group Manager Matthew Thornton blends fuel additives at NREL's ReFUEL Lab.



A Consortium to the Rescue

The National Advanced Biofuels Consortium (NABC), which NREL and Pacific Northwest National Laboratory (PNNL) have co-led on behalf of the U.S. Department of Energy since early 2010, has been tasked with solving some of the challenges surrounding drop-in biofuel technology. The NABC has a three-year charter to winnow down the list of possible biomass conversion technologies, and to prepare one or two processes for scale-up to the pilot scale—a critical step for commercializing the process.

While NREL and PNNL are leading the effort, the consortium also includes three other national laboratories, four universities, and corporate partners that range from small start-up technology companies to major oil refiners including Tesoro and BP North America.

“The NABC is a two-stage effort,” said Tom Foust, director of the NABC. “Stage one was to evaluate the landscape of promising hydrocarbon fuel production technologies from biomass and down-select to the ones that looked the

most promising. Stage two is an ongoing two-year effort to develop those promising technologies to a pilot-ready state.”

In its first year, the NABC investigated six process options for creating drop-in biofuels, narrowing the list to two main processes. The first involves fermenting biomass sugars, in a process similar to making beer, which is also the way that fuel ethanol is produced today. Fermentation uses yeast or some other microorganism to convert the sugars, and although it usually produces ethanol, the NABC is investigating fermentation processes that can generate diesel fuel.

Amyris, an integrated renewable fuels company, is leading this investigation, which uses a bioengineered yeast to produce farnesene. This 15-carbon molecule is one that can be converted into diesel fuel.

The second process the NABC is investigating is the catalytic conversion of sugars to fuels. Because this process relies on a chemical conversion, it completely avoids the use of microorganism. With the help of catalysts, a company called Virent Energy Systems has been able to produce the full trinity of major transportation fuels.

By the fall of 2013, the NABC will finish preparing these technologies for pilot scale, including conducting detailed engineering studies and environmental impact analyses.

“STAGE ONE WAS TO EVALUATE THE LANDSCAPE OF PROMISING HYDROCARBON FUEL PRODUCTION TECHNOLOGIES FROM BIOMASS AND DOWN-SELECT TO THE ONES THAT LOOKED THE MOST PROMISING. STAGE TWO IS AN ONGOING TWO-YEAR EFFORT TO DEVELOP THOSE PROMISING TECHNOLOGIES TO A PILOT-READY STATE.”



Photo by Dennis Schroeder, NREL

Researcher Bob Lyons draws fermentation samples from a 9,000-liter fermentation vessel at NREL's Integrated Biorefinery Research Facility.



NREL's Integrated Biorefinery Research Facility has a 27,000-ft², high-bay biochemical conversion pilot plant that can accommodate bench-to-pilot-scale processes for converting cellulosic biomass into a variety of fuels and chemicals—processes that can go through up to one ton of dry biomass per day.

Substitutes for Crude Oil

The NABC is also working to address the main technical challenges faced by two additional processes that produce crude oil substitutes: hydrothermal liquefaction and hydropyrolysis.

Hydropyrolysis is a version of pyrolysis, where heating biomass in the absence of oxygen yields an oily liquid. Hydropyrolysis adds pressurized hydrogen and specially tailored catalysts to the reactor, causing reactions that yield more of the “light” (small-chained) hydrocarbons that are found in gasoline and jet fuel.

Hydrothermal liquefaction, on the other hand, involves immersing the biomass at high temperature in water in the presence of catalysts or reactants to speed the reaction and control the final product. The reaction vessel is held at high pressure to keep the water from boiling.

Both hydrothermal liquefaction and hydropyrolysis show promise, but they aren't quite to the point where they could be scaled up to the pilot level. Rather than give up on the technologies, however, the NABC is trying to address the main technical challenges that are holding them back. The consortium aims to solve these challenges by the time its charter ends in late 2013.



Congressional staff learn about biofuel research technology during a recent tour of NREL's lab facilities.

NREL and the NABC

The NABC is obviously conducting important research in drop-in biofuels, and NREL is the lead organization for the NABC. But what, specifically, does NREL contribute? That question has several answers.

NREL's main hardware contribution is the use of its new pilot-scale biofuels facility, the Integrated Biorefinery Research Facility, where the biomass is treated and prepared for conversion into fuels. NREL's decades of experience in pretreatment technologies for converting biomass to ethanol is also relevant for drop-in biofuels.

However, NREL's most significant contribution to the NABC may be its ability to perform rigorous technical and economic analyses of the various chemical pathways and technologies that are under examination.

"NREL acted as a gatekeeper for the technologies," Foust explained. "It's very difficult to do that in a research environment because you have to define criteria, you have to have rigorous standards, you have to have complete transparency, you have to be unbiased, you have to have rigor in your economic analysis, and you have to have consistency. NREL did an exceptional job."



PHOTO COURTESY OF Dennis Schroeder, NREL

Looking Ahead: NREL to Ramp Up its Drop-In Biofuels Research

The NABC's work will be done by early in 2014, but its impact on NREL will be long lasting. For many years NREL has been a leading research organization in the conversion of biomass to ethanol, but as that technology matures, the lab is setting its sights on new goals. Most of the future emphasis will be on drop-in biofuels, which means that in a sense, the NABC came along at a perfect time for NREL.

"Starting in 2013, we're shifting the focus from cellulosic ethanol to drop-in biofuels," Foust said. "The NABC did a really nice job of setting the stage, giving us the research and the partnerships that we need to transition the whole program as seamlessly as we can."

— Written by Kevin Eber

NREL'S ADDITIONAL WORK ON DROP-IN BIOFUELS

The NABC is currently driving much of NREL's research in drop-in biofuels, but the laboratory is also conducting other drop-in biofuel-related projects:

- ▶ **CORN STOVER TO JET FUEL.** While Virent has partnered with NREL through the NABC, the company also recently won a \$13.4 million contract from the U.S. Department of Energy to develop a process that converts corn stover (the non-edible parts of corn) into jet fuel.

NREL is named as a partner in Virent's contract and is providing the pretreatment technology that breaks down the corn stover through a combination of pressure, steam, and chemicals.

NREL is also studying the fundamental properties of the proprietary catalysts Virent uses, as well as providing a techno-economic analysis of its process to ensure that it will yield a cost-competitive product. The Idaho National Laboratory is also participating in the project by providing the corn stover.

- ▶ **BIOMASS TO JET FUEL.** NREL recently worked with start-up company Cobalt Technologies to convert biomass into butanol, which can, in turn, be converted into jet fuel. Cobalt used NREL's Integrated Biorefinery Research Facility to scale its process to pilot scale.
- ▶ **CLEANING HOT GAS.** NREL has developed and patented a catalyst that can help clean the hot gas that results from gasifying biomass, and continues to work with enzyme manufacturers to develop new and better enzymes to help release the sugars from biomass.

- ▶ **OIL-RICH ALGAE.** NREL has revived one of its early research projects, which aimed to develop strains of algae that are high in lipids, or oils.

"NREL is doing a lot of strain development for algae, working on having the algae accumulate more lipids," said Rich Bolin, a senior project leader at NREL. "We've started to think about the composition of the lipids, altering those so that you're getting more desirable lipids in the diesel, gasoline, or jet fuel range so you don't have to upgrade it as much."


- ▶ **COMMERCIAL FEASIBILITY OF BIOMASS FUELS.** NREL researchers are also exploring if, and at what levels, biomass-derived oxygenates, or fuels containing residual oxygen, are scientifically and commercially feasible in drop-in fuels for both diesel and gasoline applications. This is the first project to fully assess how biomass-derived oxygenates function during storage, handling, and end use.

The wide-ranging assortment of work may seem in some ways like a smorgasbord, but that's somewhat by design, because it keeps NREL's researchers fluent in all the available technologies.

"We're not really here to choose winners," Bolin said. "We're here to look at all the options and to see scientifically which ones are going to work, and which ones are not."



NOT TOO HOT,



Mythological character Icarus' melted wings sent him plummeting to earth when he ignored his father's advice and flew too close to the sun. Heat was Icarus' undoing. Today's real-world electric-drive vehicles (EDVs) also require diligent attention to temperature. The battery, power electronic system, electric motor operating temperatures, and climate control all factor into an EDV's performance, range, lifespan, affordability, and—most importantly—driver acceptance.

NOT TOO COLD

Thermal management technologies increase vehicle energy efficiency and performance while reducing costs.

LAST YEAR, U.S. consumers drove more than 487,000 EDVs (hybrid, plug-in hybrid, and all-electric vehicles) off dealers' lots. But most of these vehicles still cannot match the price, driving range, and refueling speed Americans have come to expect from gas-powered automobiles. Issues with thermal management cause some of these limitations.

At the same time, as the U.S. auto industry grapples to meet ambitious new government fuel economy regulations, the U.S. Department of Energy (DOE) and the cross-agency EV Everywhere Grand Challenge initiative have set goals for EDVs that more than double driving range, cut battery and electric drive system costs by 75%, and use less energy to achieve the same level of climate control.

Heavy-duty vehicles account for 26% of national transportation sector petroleum consumption. Manufacturers and operators alike are looking to new thermal management strategies to cut

fuel use, lower costs, and meet regulatory requirements.

Experts at the National Renewable Energy Laboratory (NREL) are working closely with industry partners to address these thermal management challenges, spark greater consumer interest in EDVs, and put more fuel-efficient trucks on the road. Their research focuses on dramatically increasing energy efficiency, improving reliability, and decreasing emissions and cost, while maximizing vehicles' appeal to consumers.

"We can only meet new fuel-economy standards of 54.5 mpg by 2025 if we use a wide range of strategies, including broader deployment of electric vehicles," says Chris Gearhart, director of NREL's Transportation and Hydrogen Systems Center. "And we'll only be able to get drivers in those cars if we solve the temperature puzzle."

Batteries: Longer Range at a Lower Cost

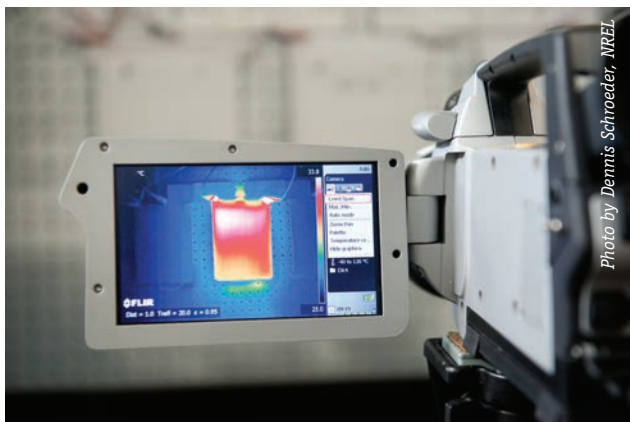
Often the most expensive of EDV components, batteries need to be affordable, high-performing, and long-lasting to make these vehicles attractive to more consumers. According to EV Everywhere, if EDVs are to gain market share, batteries will have to cost less by a factor of 4 but take drivers twice the distance on a single charge. Understanding thermal characteristics is crucial to meeting these goals.

NREL, as a recognized leader in battery thermal management research and development (R&D), evaluates battery cells, modules, and packs. The lab's thermal behavior, capacity, conductivity, lifespan, and overall performance assessments factor in the impacts of full-system integration.

"The industry, with support of NREL and DOE, has made incredible progress—10 years ago these batteries were almost triple the cost and three times the size, but could only move a car half the distance," says NREL Energy Storage (ES) Group Manager Ahmad Pesaran. "That said, we still have a long way to go."

The laboratory's tests for the U.S. Advanced Battery Consortium show that optimized thermal management can increase battery power by more than 20%. Without proper thermal management, an EDV battery that can last almost 15 years in a temperate climate, like in Minnesota, lasts only seven years in a hot climate, such as in Arizona. In extreme instances, battery overheating can lead to issues such as those that have plagued the Boeing 787 Dreamliner, resulting in fire and, in rare cases, explosion of the battery material.

NREL's breakthrough research is focused on reducing thermal resistance of components to achieve more uniform temperatures. NREL uses its R&D 100 Award-winning Isothermal Battery Calorimeters, the only instruments in the world capable of such precise thermal measurements, for much of this research. NREL is also working with industry to develop computer-aided engineering software tools to optimize thermal management of batteries.



NREL researchers use thermal imaging to evaluate thermal properties of a lithium-ion battery pack.

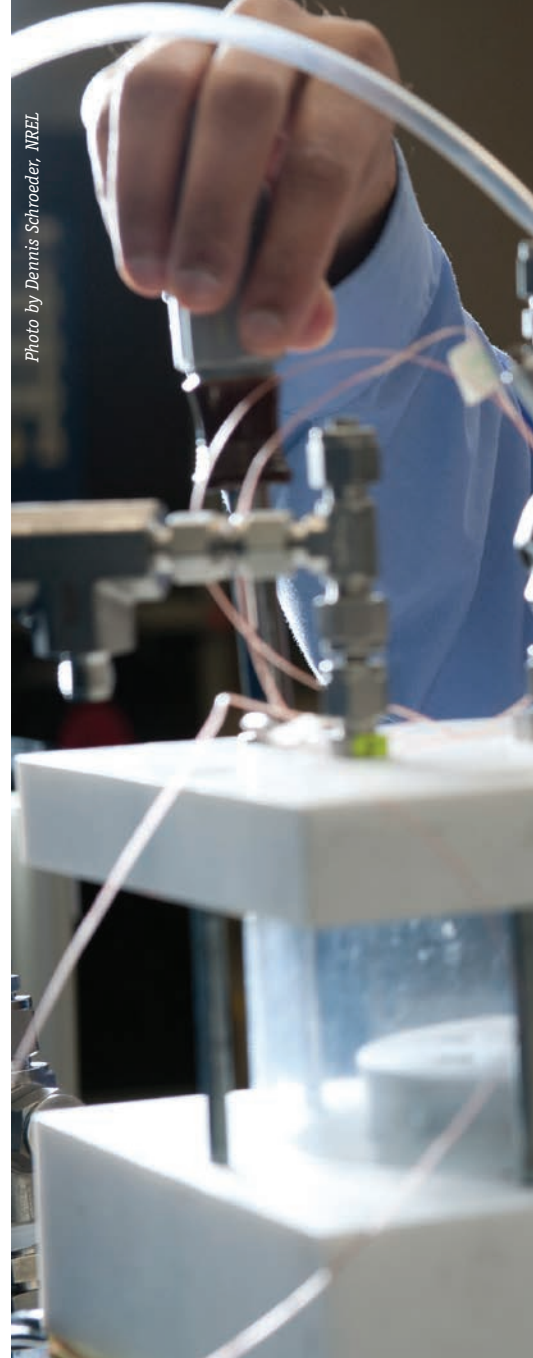


Photo by Dennis Schroeder, NREL

"THE INDUSTRY, WITH SUPPORT OF NREL AND DOE, HAS MADE INCREDIBLE PROGRESS—10 YEARS AGO THESE BATTERIES WERE ALMOST TRIPLE THE COST AND THREE TIMES THE SIZE, BUT COULD ONLY MOVE A CAR HALF THE DISTANCE..."

Photo by Dennis Schroeder, NREL



Researcher Sreekant Narumanchi examines the performance of a cooling loop in NREL's Advanced Power Electronics Lab.

Power Electronics and Motors: Reduced Size, Weight, and Cost

Power electronics, which run a wide range of systems in conventional automobiles, are essential to EDV performance. Unfortunately, technology has yet to meet the demands of a mass-market audience.

Dramatic advances in power electronics and electric motors (PEEM) will be required to meet the EV Everywhere initiative's affordability and performance targets. Boosting electric-drive system efficiency, while reducing cost by 75%, and size and weight by more than 35%, will rely heavily on improved thermal management.

In EDVs, power electronics control the flow of electricity between the battery, the motor, and other powertrain components. The PEEM team improves thermal performance

of components and systems through modeling, testing, and analysis. This leads to cooling systems and packaging materials that meet energy efficiency, performance, and reliability targets.

"Some of this technology has already been applied to commercially available components," says Advanced Power Electronics and Electric Motors Task Lead Sreekant Narumanchi. "We continue to work with partners in helping make PEEM components lighter, smaller, and less expensive, eventually helping make EDVs more competitive in the marketplace."

Climate Control: Improved Range and Thermal Comfort

Climate control systems such as air conditioners and heaters make both conventional vehicles and EDVs more comfortable. At the same time, electrical energy consumed for climate control can significantly reduce EDV range—in some cases by as much as 68%.

Conventional vehicles heat cabins with engine waste heat, but EDVs do not have an engine, which presents climate control challenges for automobile manufacturers. Using the battery for cabin heating takes valuable energy away from propulsion.

By improving thermal management, NREL researchers believe they can increase EDV range by 10% during operation of the climate control system. In collaboration with the automotive industry, the lab is exploring thermal load reduction technologies and improving efficiency while maintaining the thermal comfort that drivers expect. Strategies include:

- ▶ Zone-based cabin temperature controls
- ▶ Advanced heating and air conditioning controls
- ▶ Seat-based climate control
- ▶ Thermal load reduction
- ▶ Thermal preconditioning.

"The impact of climate control on an electric vehicle can be significant depending on the temperature and driving conditions," says John Rugh, task leader for Vehicle Thermal Management. "Our work with industry partners aims to minimize energy for climate control so the battery can be used to power the wheels."

Integrated Thermal Management: Closing the Loop

By working to reduce the cost and increase the efficiency of EDV cooling systems, NREL is helping the automotive industry move closer toward the goals of extending battery life and driving range between charges, while improving safety, reliability, and comfort.

Vehicles with internal combustion engines use radiators and oil coolers to remove heat from the engine and transmission. EDVs, however, require more complicated systems to meet the additional thermal demands of power electronics and energy storage systems.

Using thermal testing and analysis, NREL is evaluating the potential benefits of combining the PEEM and ES cooling loops with the engine cooling and passenger compartment climate control systems. Reducing the number of cooling systems and related components can translate into lower component and maintenance costs, less weight, reduced aerodynamic drag, and ultimately better fuel economy and range.

NREL's thermal model of a compact-sized EDV has reduced total vehicle thermal management power consumption by combining cooling loops and using waste heat from PEEM components. Combined cooling loops use refrigerant-to-liquid heat exchangers, creating a more efficient system with improved heat transfer, as well as providing liquid to cool PEEM and ES systems.

A vehicle undergoes thermal testing on NREL's VTIF test pad.





Photo by Dennis Schroeder, NREL

TECHNOLOGY TO MARKET:

Isothermal Battery Calorimeters Help Developers Improve Vehicle Battery Performance, Lifespan, and Safety

Developed by NREL in collaboration with industry partner NETZSCH, the R&D 100 Award-winning Isothermal Battery Calorimeters (IBCs) are the only ones in the world capable of performing the precise thermal measurements—with 98% accuracy—needed to make safer, longer-lasting, and more cost-effective lithium-ion batteries. Such precise heat-generation measurements are crucial for optimizing battery thermal-management systems to extend battery life and improve safety at affordable cost.

Lithium-ion batteries are widely considered the leading energy-storage option for electric-drive vehicles, but extreme temperature swings can diminish their performance, lifespan, and safety. Diagnostics performed using the IBCs provide the foundation for developing new thermal-management techniques that ensure the batteries meet warranty specifications and provide sufficient power.

The IBCs' patent-pending innovations—complete thermal isolation, the ability to test large cells and batteries, and the features necessary for testing high-power batteries safely—provide battery integrators with a level of accuracy and functionality not available in other calorimeters.

Made possible thanks to support from the U.S. Department of Energy's Vehicle Technologies Office, NREL's 15-year history of developing isothermal battery calorimeters and generating thermal data has helped the U.S. battery industry develop systems with better thermal performance. NETZSCH is in the process of commercializing the IBC technology following a 72% year-over-year jump in sales of hybrid-electric and plug-in vehicles.

In addition to earning a 2013 R&D 100 Award, which ranks the instruments among the year's most significant innovations, the IBCs were recognized with a 2012 Governor's Award for High Impact Research.

— Written by Julia Thomas

Photo by Dennis Schroeder, NREL



In NREL's Advanced Power Electronics Lab, liquid cooling equipment is used to evaluate heat transfer in vehicle components.

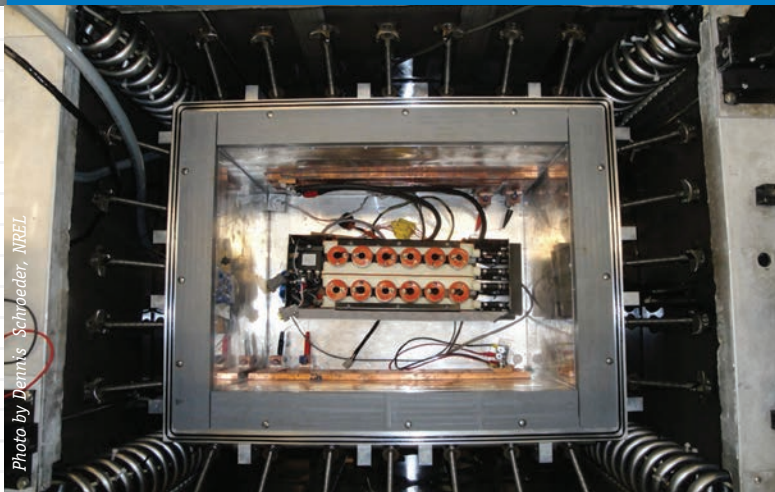
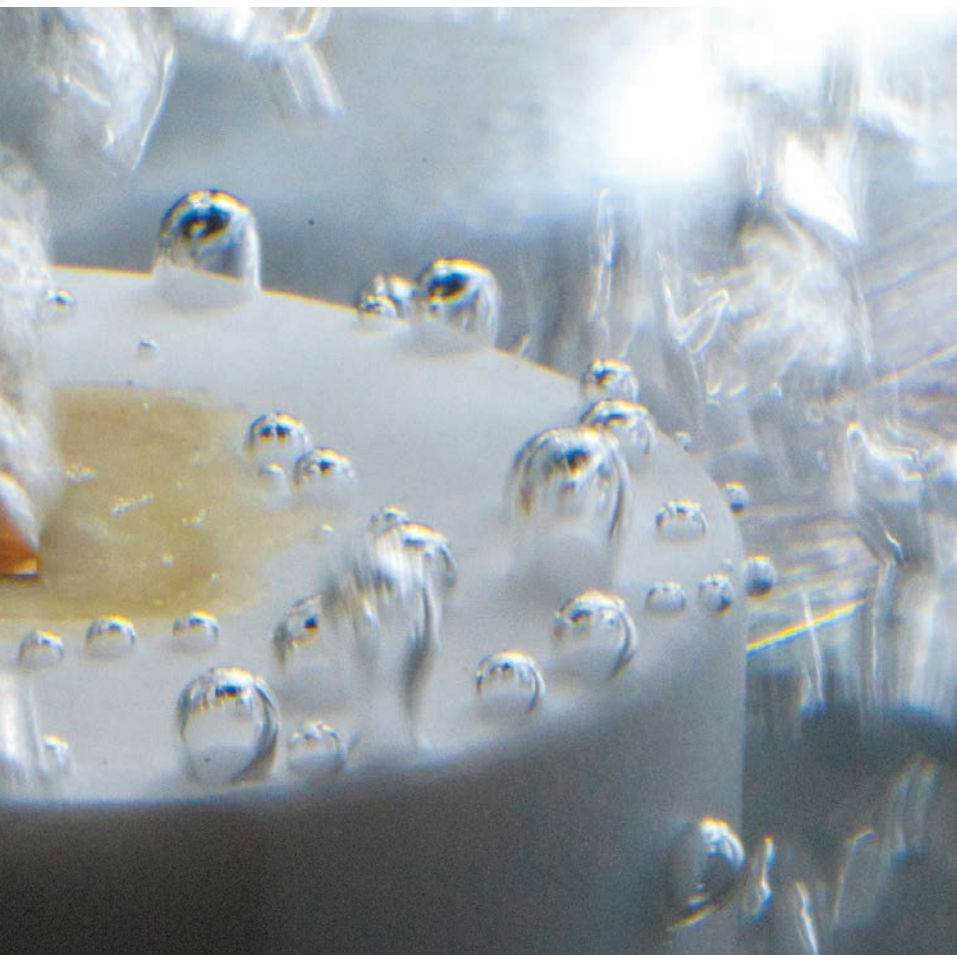


Photo by Dennis Schroeder, NREL

As shown here, the test chamber of the large-volume IBC is big enough to accommodate the sizeable battery modules used in electric-drive vehicles.

"IF WE CAN DEMONSTRATE A THREE-YEAR OR BETTER PAYBACK PERIOD WITH RELATIVELY LOW RISK ON THESE TECHNOLOGY INVESTMENTS, TRUCK OPERATORS WILL BE ECONOMICALLY MOTIVATED TO ADOPT THE TECHNOLOGIES."



absorb heat. The large painted surfaces of heavy-duty trucks further increase this effect. NREL researchers measured a 20% decrease in daily electrical air-conditioning system energy consumption after switching a truck's color from black to white. Engineers are also investigating advanced paints that look like darker colors, but thermally behave like lighter colors, giving truck fleets greater flexibility in selecting paint colors without sacrificing efficiency. Insulation is a factor as well. NREL tests have shown a 34% reduction in truck sleeper climate control loads using advanced methods of insulation.

Researchers and outside partners use NREL's CoolCalc and CoolSim modeling tools to simulate energy used for climate control in truck cabs and calculate the potential benefits of thermal load reduction options in a range of use and weather scenarios. The tools make it possible to rapidly evaluate the impact of factors such as insulation thickness, material properties, and geometries on climate control loads over the wide range of weather conditions experienced in real-world operation and identify the most promising solutions.

Heavy-Duty Vehicles: Decreased Energy Loads

Light-duty EDVs are not the only vehicles that can benefit from improved thermal management. According to an Argonne National Laboratory report, each year in the United States, long-haul trucks consume approximately 838 million gallons of diesel fuel for rest-period idling, much of which is used for heating and air conditioning. DOE's SuperTruck program has set a goal to improve heavy-duty vehicle fuel economy 50% by 2015, and addressing thermal management and climate control loads will be essential in achieving this. Working closely with industry partners, NREL's CoolCab program has shown that improved cab thermal management can reduce climate

control loads and associated costs. This could cut fuel consumption, emissions, and operating costs.

"If we can demonstrate a three-year or better payback period with relatively low risk on these technology investments, truck operators will be economically motivated to adopt the technologies," says Jason Lustbader, CoolCab task leader. "Our goal is to bring down climate control loads by at least 30%."

Using truck cabs located on the Vehicle Testing and Integration Facility (VTIF) test pad, researchers investigate a wide variety of cabin thermal management technologies. Engineers quantify the impacts of different materials and equipment—films, paints, radiant barriers, and idle reduction technologies—on climate control loads.

As anyone who has been in a car on a sunny day can attest, dark paint colors

Turning Widespread EDV Adoption from Myth into Reality

NREL researchers are working to turn widespread adoption of energy-efficient vehicles from a myth into reality.

Improving thermal management will result in the enhanced performance and reduced costs needed to motivate more drivers and operators to adopt EDVs and energy-efficient trucks. And that is likely to lead to a happy ending for consumers, the economy, and the environment.

— Written by Anya Breitenbach

ELECTRIC VEHICLE BATTERY DEVELOPMENT GAINS MOMENTUM

CAEBAT collaboration targets EDV batteries with longer range and lifespan, at a lower cost.

"WHEN people get behind the wheel of an electric car, it should be a great driving experience. Period." Dr. Taeyoung Han, GM technical fellow, said, "Battery performance is vital in meeting drivers' expectations."

Electric-drive vehicles (EDVs) promise to curb greenhouse gas emissions and slash America's need for imported oil. However, designing high-performance, cost-effective, and safe energy storage systems can present considerable challenges.

Batteries, which are typically some of the most expensive EDV components, power the motor and other electrical systems, while storing grid-fed energy as well as kinetic energy from regenerative braking. To appeal to drivers, electric cars need to have a range of 250 to 300 miles between charges, placing greater pressure on the vehicles' battery packs.

At the same time, for EDVs to gain meaningful market share, the U.S. Department of Energy (DOE) has determined that battery costs need to be cut from \$400-\$600 per kilowatt hour (kWh) to \$125/kWh, and battery lifespan needs to be extended to 15 years from its current eight years.

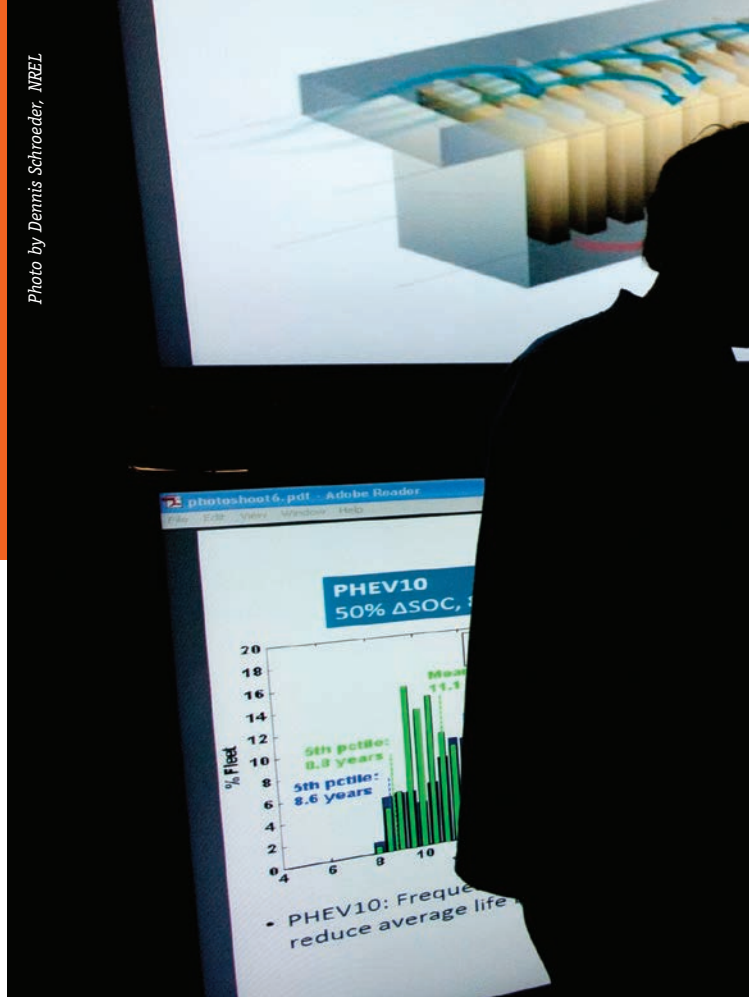
POWERING BETTER PERFORMANCE, LOWER COSTS

To accelerate development of battery packs and wider adoption of EDVs, the National Renewable Energy Laboratory (NREL) is collaborating with a range of experts on the \$14 million Computer-Aided Engineering for Electric Drive Vehicle Batteries (CAEBAT) project.

CAEBAT's goal is to develop sophisticated software tools to improve and accelerate battery design and boost EDV performance and consumer appeal — and ultimately diminish petroleum consumption and polluting emissions.

"Lithium-ion batteries are widely seen as the most feasible solution for electric vehicles in the next decade, but so far high cost, limited range, and long recharge times have been stumbling blocks for making electric vehicles realistic options for the broader market," said NREL Energy Storage Group Manager Ahmad Pesaran.

Photo by Dennis Schroeder, NREL



"Researchers and industry engineers need to work together to speed up advancements in performance while lowering costs," Pesaran went on to explain. "Even if a cell is developed that meets most of the EV requirements, a full battery pack consisting of many cells needs to meet the challenges posed by full system integration and operation under real world conditions."

The CAEBAT project addresses these issues with a suite of battery cell and pack engineering tools that:

- ▶ Investigate a full range of chemistry, cell design, and battery pack options for particular vehicle platforms
- ▶ Factor in electrochemical, thermal, and mechanical interactions
- ▶ Shorten battery prototyping and optimization processes
- ▶ Improve overall battery performance, safety, and lifespan
- ▶ Reduce costs for suppliers, manufacturers, and consumers.

To appeal to drivers, electric cars need to have a range of 250 to 300 miles between charges, placing greater pressure on the vehicles' battery packs.



NREL's modeling, simulation, and testing activities include battery safety assessment, next-generation battery technologies, material synthesis and research, subsystem analysis, and battery second use studies.

COMBINING ENERGY IN INDUSTRY-RESEARCH PARTNERSHIP

"We need to keep raising the bar with our electric car designs, and battery performance is a huge part of that," said Xiao Guang Yang of Ford, a CAEBAT principal investigator.

Most battery models and simulation tools developed prior to CAEBAT did not strike the balance of precision and ease-of-use battery developers, pack integrators, and automakers require. In 2011, DOE/NREL used a competitive procurement process to select three teams to develop three separate, competitive, validated, and easy-to-use CAEBAT software tools for battery pack design. The three teams include representatives from each key industry sector:

- ▶ EC Power, Penn State University, Johnson Controls, and Ford
- ▶ General Motors, ANSYS, and ESim
- ▶ CD-adapco, Battery Design LLC, A123 Systems, and Johnson Controls.

While DOE's Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office provided primary funding for this activity, these industry partners contributed 50% (\$7 million) of the project budget.

MODELING AT THE MATERIALS, CELL, AND PACK LEVEL

At the outset of the CAEBAT project, NREL unveiled a development crucial to filling a gap in existing tools: a predictive computer simulation of Lithium-ion batteries. This framework, known as the Multi-Scale Multi-Dimensional model, has a modular, flexible architecture that connects the

physics of battery charge/discharge processes, thermal control, safety, and reliability in a computationally efficient manner. This makes it much easier to independently develop submodels at the cell and pack levels.

NREL provides technical support on electrochemical and thermal modeling to all of the CAEBAT teams as they work independently to develop and validate computer-aided engineering tools based on a variety of chemistries, cell geometries, and battery pack configurations.

CAEBAT has already produced models of alternatively stacked, wound-, and large-format cylindrical cell performance, as well as pack thermal networks. These models have been validated from the cell to the pack level. The software tools that have resulted from this collaboration are expected to become competitive marketplace offerings for battery engineers and EDV designers by the end of 2014.

"The simulation and automation tools that will come out of this project will impact the industry's ability to design energy storage systems at a faster pace," said Brian Sisk, director of Controls and Modeling for Johnson Controls Power Solutions. "We also believe this work will enable innovation in battery pack design and technology integration, leading to better electric vehicle performance."

In addition to computer-aided engineering and groundbreaking thermal evaluation and analysis, NREL also acts as a go-to resource in boosting efficiency and troubleshooting deficiencies in energy storage systems. This helps automakers and battery companies design better vehicles and meet challenging cost and performance targets.

— Written by Anya Breitenbach



Dynamometer testing at NREL's ReFUEL Lab helps researchers determine the fuel economy and emissions benefits of hybridization.

THE KEY TO GREENER FLEETS

Leveraging state-of-the-art technology to revolutionize fleet sustainability and energy efficiency.

GREEN is more than a color of paint for truck fleets. These

days, going "green" means reducing petroleum consumption by leveraging the smartest alternative vehicle technologies in the marketplace.

Industry leaders from Coca-Cola to FedEx, as well as many government agencies, are looking to do just that by turning to the National Renewable Energy Laboratory (NREL) for transportation expertise, not to mention research, data, tools, and deployment support.

"Our work provides unbiased, third-party data as well as tools and processes to help fleets understand what works or doesn't work," said NREL's Kevin Walkowicz, manager of the Testing and Analysis Group in the Transportation and

Hydrogen Systems Center. "You can use resources to build technology, purchase technology, or figure out how to best use technology."

Fleet managers across the country use NREL evaluations to operate medium-duty vehicles (MDV) and heavy-duty vehicles (HDV) more energy efficiently and cost effectively. At the same time, NREL supports the Federal Energy Management Program (FEMP) as the agency looks at fuel consumption by a broad range of light-duty vehicles across 16 participating federal agencies.

NREL TOOLS DECODE FLEET DNA, SECURELY STORE DATA

One popular tool that NREL has developed is Fleet DNA, which allows users to access fleet vehicle usage data summaries and drive-cycle visualizations. The Web-based tool now offers the "genetics" for six MDV and HDV truck vocations, or uses, ranging from delivery vans to school buses.

Eventually, these categories will be broken into subsets, and users will be able to select data not just for vans, but for specific types of vehicle, such as those used for food, flower, or linen delivery. The National Truck Equipment Association is using the Fleet DNA tool to better understand which technologies work best in specific vocations.

Tools such as Fleet DNA all rely on accurate, real-world data—and gathering data is a major part of the work NREL does in the transportation sector. Since October, 2011, NREL researchers have been documenting the performance of electric and plug-in hybrid MDV trucks.

In addition, to help commercialize electric vehicles and the electric charging infrastructure they require, NREL processes and securely stores

metrics from some 800 alternative fuel vehicles, all of which were deployed using funding by the American Recovery and Reinvestment Act.

The resulting quarterly reports are a treasure trove of information—offering insights into how much electricity the vehicles used, when it was used, and what energy savings resulted from the fleets going electric.

In 2012, NREL's Fleet Test and Evaluation team finished a yearlong evaluation of hybrid electric delivery trucks operated by Coca-Cola Refreshments in Miami, Florida. The team analyzed fuel economy, maintenance, and on-road performance data for five electric and five conventional diesel trucks. On-road tests showed the hybrids demonstrated a 13.7% higher fuel economy than their conventional counterparts.

These same vehicles were also tested at NREL's Renewable Fuels and Lubricants (ReFUEL) Laboratory to determine fuel economy and emissions benefits from hybridization. During dynamometer testing at ReFUEL, the hybrids demonstrated up to a 30% improvement in fuel economy, depending on how they were driven.

Others companies, including FedEx and Frito Lay, are collaborating with NREL to test hybrids and other advanced technologies in their fleets.

SECURE DATA, EVOLVING TOOLS, EFFICIENT DRIVING

NREL's Transportation Secure Data Center (TSDC), which focuses on light-duty consumer vehicles, also provides essential information to further the research. Because the TSDC provides privacy protection for dataset participants, it has access to "scrubbed" data that spotlights actual on-road patterns.

"Understanding how people drive in the real world is important," explained Jeff Gonder of the Transportation and Hydrogen Systems Center.

High-level summary statistics, participant demographics, and second-by-second speed profiles are among the types of data

Photo by Dennis Schroeder, NREL



Trucks undergo thermal analysis at NREL's Vehicle Testing and Integration Facility (VTIF). The VTIF is used to explore climate control load reduction methods for light- and heavy-duty vehicles.

users can download from the site. Users can also tap into spatial data through a secure portal after completing a simple application and approval process.

NREL is also continuing to refine its FEMP Fleet Sustainability Dashboard, or FleetDASH tool. This customizable dashboard tracks fleet fuel consumption, greenhouse gas emissions, and vehicle inventories by participating federal agencies, including most Department of Defense branches, land management agencies, and others. Users can search by sub-fleet or individual vehicle to check on fuel purchases. When there is a missed opportunity to purchase alternative fuel, the interactive site displays an alternative fuel site location.

And while looking at 170,000 light-duty vehicles may seem a very different science from conducting MDV and HDV studies, Federal Fleet Project Leader Ryan Daley said, "They are two different ways of attacking the same problem—getting the best fuel technologies on the road."

In the future, these efforts may become more intertwined as NREL continues its transportation leadership and the greening of fleets across the United States.

—Written by Ernie Tucker



NREL engineers Jonathan Burton and Petr Sindler monitor data from a test being run on the chassis dynamometer at the ReFUEL Lab.

PUTTING ON THE BRAKES TO PROTECT AMERICA'S NATURAL TREASURES

National Parks Initiative greens roads and preserves once-in-a-lifetime experiences.

NATURAL WONDERS. Fresh air. Wide open vistas. Each year, more than 280 million travelers seek adventure and inspiration at America's national parks. But all too often, what should be once-in-a-lifetime experiences are marred by traffic congestion and poor air quality. Visitors find themselves frustrated by clogged roads and obscured views of some of our most scenic natural and cultural resources.

In Yellowstone alone, 3.6 million geyser-spotters and bison-watchers arrive by car during the park's 6-month peak season. Ozone pollution in Rocky Mountain National Park can reach levels higher than in nearby Denver, Colorado, cutting visibility nearly in half.

The U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL), and the National Park Service (NPS) are collaborating to develop sustainable transportation strategies. These strategies will reduce petroleum-based fuel consumption and greenhouse gases (GHGs), while enhancing the park experience.

The Clean Cities National Parks Initiative supports the NPS Green Parks

Plan with transportation projects that deploy alternative fuels, electric-drive vehicles, and fuel-saving measures. These operational approaches are paired with guest outreach stressing the environmental, economic, and health benefits within the parks and the world beyond.

SUSTAINABLE TRANSPORTATION REACHES ACROSS—AND BEYOND—PARKS

"Together, we are today's conservation visionaries, partnering to ensure we can preserve these national treasures for future generations," says Mary Hazell of NPS Sustainable Operations and Climate Change. "Sure, the Clean Cities National Parks Initiative helps us accomplish projects. More importantly, the partnerships create synergy for action at the local level with neighbors, partners, and businesses that can really make a difference."

Thirteen NPS locations have joined the initiative:


- ▶ Yellowstone, Denali, Grand Teton, Mesa Verde, Shenandoah, Mammoth Cave, and Rocky Mountain National Parks
- ▶ Blue Ridge Parkway
- ▶ Golden Gate National Recreation Area
- ▶ National Mall and Memorial Parks
- ▶ San Antonio Missions National Historical Park
- ▶ Mississippi National River and Recreation Area
- ▶ Sleeping Bear Dunes National Lakeshore.

Partners are selected based on the potential for cost-effective reductions in petroleum use and GHG emissions, use of readily-available alternative fuels, public visibility, and growing local collaboration. The initiative builds on programs that have already been established at parks including Grand Canyon, Glacier, Zion, Great Smoky Mountains, Acadia, and Crater Lake.



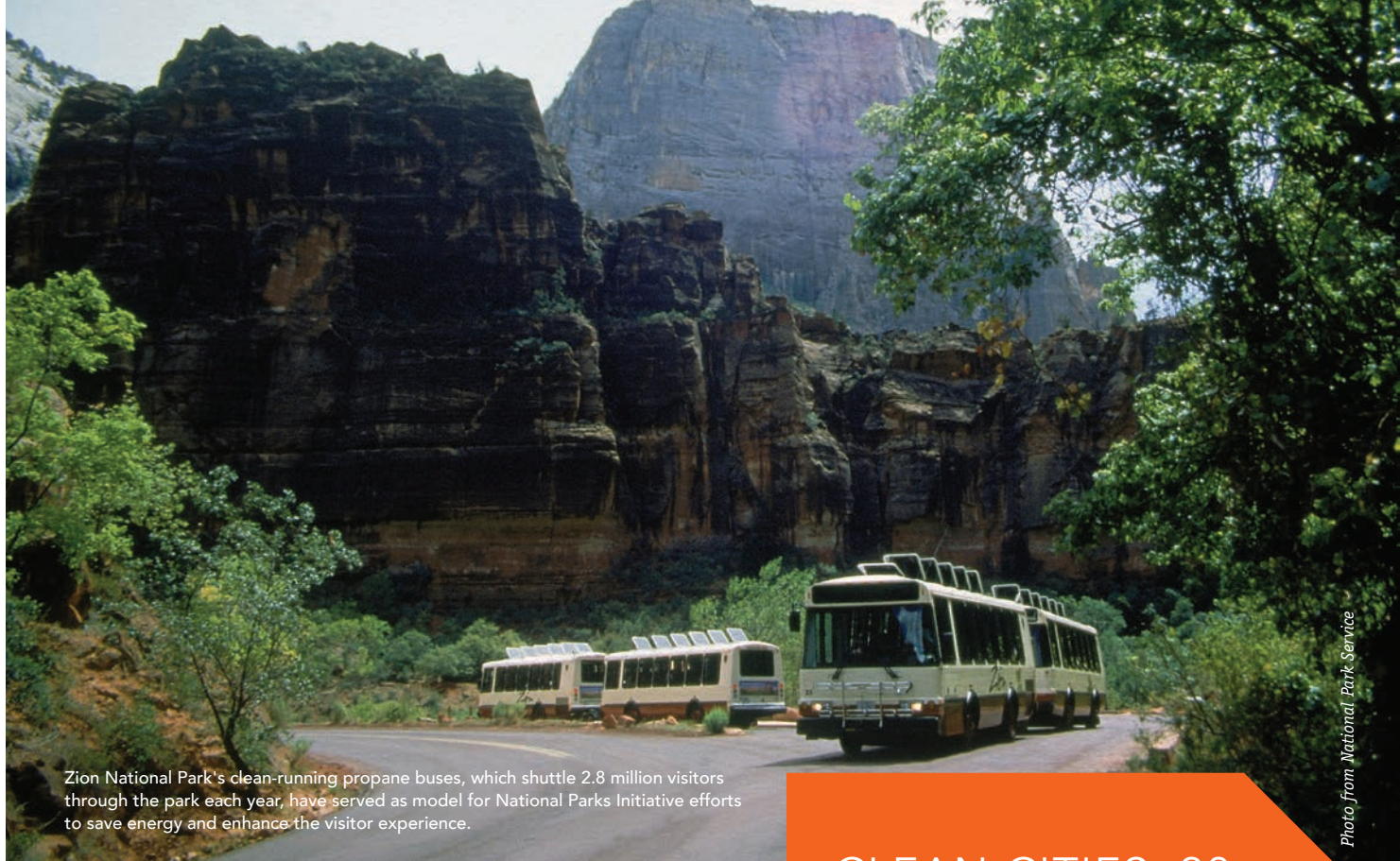
Photo by Julie Sutor, NREL

A plug-in electric vehicle charges near the Thomas Jefferson Memorial in Washington, D.C.

A scenic view of a red historic bus, likely a vintage tour vehicle, parked on a paved road. The bus is red with a black roof and has a white canopy over the rear section. It is positioned in the lower foreground, angled towards the right. The background features a vast, lush green forest covering a valley, with a prominent, rugged mountain peak rising in the distance under a clear blue sky. The scene is framed by green foliage in the foreground and sides.

"Together, we are today's conservation visionaries, partnering to ensure we can preserve these national treasures for future generations..."

One of Glacier National Park's propane-powered historic Red Buses.



Zion National Park's clean-running propane buses, which shuttle 2.8 million visitors through the park each year, have served as model for National Parks Initiative efforts to save energy and enhance the visitor experience.

Photo from National Park Service

SUSTAINABLE STRATEGIES TAILORED TO EACH PARK

The Clean Cities partnership provides NPS staff with the knowledge and tools they need to establish sustainable actions tailored to the geography, visitor patterns, and environmental considerations of each park. Energy-saving and emission-reducing strategies include:

- ▶ Promoting alternative transportation practices
- ▶ Replacing fleet vehicles with cars, trucks, buses, and maintenance vehicles powered by propane, biofuel, hybrid, natural gas, and electricity
- ▶ Promoting alternative fueling stations
- ▶ Analyzing fleet and fuel-use data to deliver targeted equipment and operation recommendations
- ▶ Providing operators with efficient driving best practices
- ▶ Implementing practices to reduce idling engines
- ▶ Educating visitors through online and printed materials, interpretive displays, programs, and personal interaction.

Where possible, Clean Cities National Parks Initiative methods and materials are being replicated across the national parks system, even in locations that are not yet formal Clean Cities partners.

"With these initial measures, we estimate that the parks have displaced more than 2.5 million gallons of petroleum-based fuel and prevented more than 23,000 tons of GHGs from being emitted," says NREL's Andrew Hudgins. "But this is really just the beginning. The projects are raising the profile of clean, cost-effective alternatives to petroleum by demonstrating these technologies to millions of visitors."

—Written by Anya Breitenbach

CLEAN CITIES: 20 YEARS OF SUCCESS IN TRANSFORMING TRANSPORTATION

Clean Cities offers industry and government partners in communities of all sizes expertise and resources in the deployment of alternative fuels, advanced vehicles, and fuel-efficient transportation measures.

Nearly 100 Clean Cities coalitions are located in communities across the United States, including areas near many national parks, national historic sites, and memorials. Since 1993, Clean Cities has saved more than 5 billion gallons of petroleum. NREL provides Clean Cities with technical expertise, training, tools, programmatic support, and information resources.

Continuum

CLEAN ENERGY INNOVATION AT NREL

Continuum is NREL's publication that showcases the laboratory's latest and most impactful clean energy innovations and the researchers and unique facilities that make it all happen.

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NREL has a history of success in scientific discovery and developing innovative technologies to meet the challenges of a clean energy future. As the only U.S. national laboratory singularly focused on advancing renewable energy and energy efficiency, NREL's mission spans the spectrum of clean energy solutions—including pioneering research in solar, wind, biomass, hydrogen, and geothermal energy. With 35 years of successful innovation from fundamental research and analysis through commercializing and deploying energy efficiency and renewable energy solutions, NREL continues to pave the way toward clean energy transformation.





National Renewable Energy Laboratory

15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

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Photo by Dennis Schroeder, NREL



A CLOSER LOOK

Take a CLOSER LOOK into NREL's drive toward a sustainable
future by visiting www.nrel.gov/closer_look